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DOI: 10.1016/j.cub.2009.03.044

Multisensory Integration: Frequency Tuning of Audio-Tactile Integration

Multisensory information can be crucial, yet in many circumstances we have little, if any, awareness of the effects of multisensory inputs on what appear to be entirely unisensory perceptions. A recent study shows robust effects of auditory input on tactile frequency discriminations and that this auditory cross-sensory interference has specific tuning.

John J. Foxe

Gentlemen, have you tried shaving with your ears plugged? Of course you haven't and perhaps this doesn't even strike you as all that difficult an undertaking, not like being asked to do it without a mirror. And goodness knows what it would be like to shave if you were asked to apply topical anesthetic to your face beforehand. Still, the next time you shave, take a little extra time to consider the sensory signals that you rely on during this tedious job. I bring up shaving here because it has often struck me just how much one relies on the combination of auditory and somatosensory inputs during this routine chore. It is a truly multisensory task and the interplay of the sound of the razor passing over unshaven areas and the feel of the blades on the skin is an excellent demonstration of the interplay of these two sensory systems during a very personal tactile roughness task. I'm not so sure that the effect is quite as strong for the opposite sex when shaving more distal and less innervated aspects of the body, but I'll assume there are reasonable parallels.

One of the earliest formal demonstrations of the role of auditory inputs on tactile sensations was also one of the most extraordinary, and is not unrelated to my shaving example. Jousmaki and Hari [1], writing in *Current Biology*, showed that by artificially altering the rubbing sounds that participants heard when asked to rub their palms together, one could dramatically alter the tactile sensations that subjects reported. They used a simple setup where they placed a microphone next to the hands and then played the rubbing sounds the hands made back through a pair of headphones. In some cases, the sounds were unaltered and in others, all frequencies above 2000 Hz were either enhanced or dampened by 15 decibels. Participants were asked to rate their tactile sensation on a scale between relative moistness (roughness) and dryness (smoothness). Two effects were seen. First, the louder the rubbing sounds were, the smoother and dryer the rubbing experience became. So, it became clear that auditory inputs could affect tactile roughness judgments. More importantly for our purposes here, they also found that by enhancing the high-frequency component (2 kHz) of the rubbing sound, the majority of their subjects also experienced a significant shift in the perceived smoothness/dryness of the skin surface. A number of the subjects spontaneously reported the rather extraordinary sensation of having a leaf of parchment paper interposed between their rubbing hands and so the effect has entered the vernacular in the multisensory field as the 'parchment-skin illusion'.

This study firmly established the role of auditory inputs as an important adjunct to tactile judgments of texture, but it also hinted that there might be a tuning function underlying this effect, as it was because of the manipulation of the high-versus-low frequency ratios of the auditory inputs that those tactile perceptions were altered. Guest *et al.* [2] corroborated this effect some years later. Participants in their study made forced-choice discriminations regarding the roughness of abrasive surfaces, and their data showed that roughness perception was modulated by the frequency content of the auditory feedback, with attenuation of high frequency inputs causing a shift in perception towards greater smoothness.

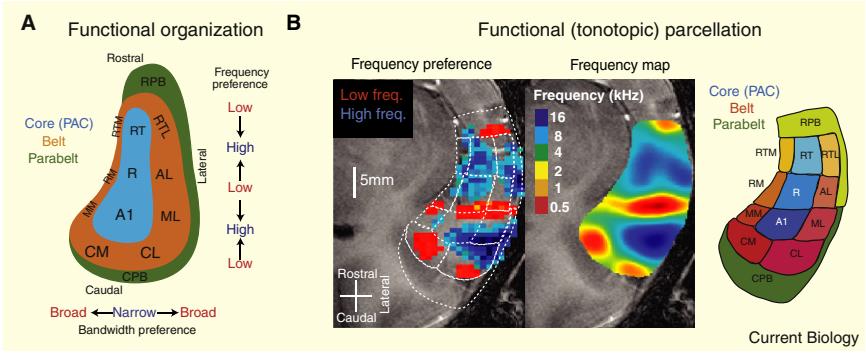

Figure 1. The organization of early auditory cortex in the macaque.

(A) Organization of monkey auditory cortex. Three primary auditory fields comprise the core region. These are surrounded by the secondary fields, the so-called belt region, and in turn by higher association areas of the so-called parabelt region. Electrophysiological studies have shown that several of these fields contain an ordered representation of sound frequency (tonotopic map, indicated on the left), and that core and belt fields prefer narrow and broadband sounds, respectively. These two functional properties can be exploited to map the layout of these auditory fields in individual subjects using functional imaging. (B) Single-slice fMRI data showing frequency-selective BOLD responses to low and high tones (left panel) and a complete (smoothed) frequency map obtained from stimulation using six frequency bands. Combining the frequency map with an estimate of the core region obtained as well as anatomical landmarks to delineate the parabelt results in a full parcellation of auditory cortex in individual subjects. (Figure kindly provided by Christoph Kayser and reprinted with permission from [14].)

Yau *et al.* [3] have revisited this issue in a series of carefully conducted psychophysical experiments. As they reported recently in *Current Biology*, they have shown convincingly that auditory inputs interfere with tactile frequency-discrimination, but not with judgments of intensity, thus ruling out an attentional confound, and that this interference only occurs when the auditory inputs are at or near the same frequency as the tactile inputs. In other words, the frequency of vibrations at the skin surface and of vibrations in the hair cells of the cochlea, two entirely separate sensory epithelia transducing two very different forms of energy, is a critical feature dimension for subsequent multisensory interactions.

Yau *et al.* [3] had participants perform a two-alternative forced-choice task where they judged which of two sequentially presented vibro-tactile stimulations of the index finger was higher in frequency. Vibratory stimuli ranged in frequency from 100 to 300 Hz in 40 Hz increments, and the second of the vibratory stimuli was accompanied by an auditory 'distractor' which could either be the same frequency as the tactile vibration or not, with frequencies ranging between 100 and 1500 Hz. The data indicated a clear decrement in the sensitivity of subjects to tactile frequency differences, but only for auditory distractors in the low frequency range. Another intriguing finding was that the perceived frequency of the tactile stimulus tended to be pulled towards the lowest frequency auditory stimulus (100Hz).

It remained possible that these interference effects were only driven by low-frequency auditory inputs, so in a follow-up experiment, the authors used a higher frequency vibro-tactile comparator stimulus (400 Hz) and showed that the interference effects also moved in a frequency-specific way. Lastly, they showed that the effects were also present for band-pass noise distractors centered at the frequency of the vibro-tactile stimulus and so, the perception of pure pitch was not necessary for the interference effect. The authors argued that this latter finding pointed to a sensory rather than decisional locus for the effect.

One obvious question that arises is why this cross-sensory effect is manifest as an impairment in tactile frequency perception. Why did same-frequency auditory inputs not aide in performance if they were integrated? Aren't performance improvements what we have come to expect when there is redundant but congruent sensory input [4–7]. Jousmaki and Hari's [1] parchment-skin findings may hold the answer. In that study, the rubbing sounds were the actual sounds of the participants own hands, and yet tactile roughness perception was changed not only by shifts in the passband of the rubbing sounds, but also by shifts in the loudness of the auditory inputs, even when the frequencies were not manipulated. In the Yau *et al.* [3] study, there is no pre-existing lawful relationship between the intensity of the auditory and vibro-tactile stimuli used. Rather, the levels chosen were experimenter controlled and were essentially arbitrary, not necessarily particularly 'realistic' in terms of similar stimuli in the natural environment. As such, it is highly likely that the auditory inputs shifted the perceived frequency of the tactile inputs, and this is in fact what is seen in the data where there is a clear shift in the perceived vibro-tactile frequency towards lower frequency auditory inputs.

One of the excellent aspects of the work by Yau *et al.* [3] is that some clear and testable predictions are made about the underlying neurophysiology. First, they argue that the effects likely occur at a sensory processing level, pointing to a region of the auditory cortex, the so-called caudo-medial belt area (CM), as the most likely substrate. This area was first implicated in auditory-somatosensory integration by Charles Schroeder [8], who showed feedforward auditory and somatosensory inputs to layer 4 in area CM of awake behaving macaques. This was considered a remarkable finding at the time since these recordings, in what was a classical region of auditory cortex, often uncovered larger somatosensory than auditory responses. It bears emphasizing that CM is just one synapse from primary auditory cortex at the second stage of the auditory hierarchy (Figure 1). Thus, robust somatosensory responses are evident at an auditory processing stage that is at the equivalent hierarchical level that V2 occupies in the visual hierarchy. Further, these inputs are just as fast as the auditory inputs to this region [9].

At the same time, my own lab had begun to uncover similarly early auditory-somatosensory interactions in early auditory cortex using both EEG and fMRI in humans [10,11]. Our initial thought was that this early integration must surely be to do with spatial mapping, but a formal test of this assumption proved us wrong [12]. Much work has been done since to try to understand the role of CM in

multisensory auditory-somatosensory processing [13] and Figure 1 shows a nice illustration of work by Christoph Kayser and colleagues [14]. This group used both intracranial recordings and functional imaging in macaques to create detailed individualized maps of the tonotopic organization of the auditory regions. One thing to note from this illustration is that area CM, which is the region implicated by Yau *et al.* [3] as the putative site for cross-frequency coupling effects between audition and touch, shows sensitivity to broad-band low-frequency stimuli and shows little or no obvious tonotopic map [15]. Thus, it may be the case that CM does not have the requisite frequency resolution to underlie these effects whereas the neighbouring CL shows a higher degree of tonotopy and may be the more likely candidate.

We have concentrated very much on these very early feedforward phases of cortical integrations in our own work [13], in no small part because these early integrations were considered by many to be so very surprising when they first came to light just a decade ago. But a reasonable question is just how 'clever' are these early integrations. How complex is the coding that occurs during initial inputs? And what of the large-scale complex of integrations that clearly occurs over the next 150 milliseconds of processing time? For example, high-density electrical mapping has been used to assess the integration of extremely basic tone-pips and monochromatic flash inputs while subjects perform nothing more complex than a reaction time task [16]. In this very simple paradigm, no fewer than six distinct phases of multisensory processing were dissociated across a wide network of cortical regions, including early extrastriate cortex, early auditory cortex, parietal regions and frontal regions. All of these distinct phases occurred within just 130 milliseconds of initial afference in area V1. So, while this study showed very early audio-visual integration in extrastriate visual areas at just 45 milliseconds, it is simply not clear what aspect of the integrative process this initial multisensory effect represents. It is certainly reasonable to think that it can hardly be a very complex operation given how early it occurs. Much remains to be done to delineate what aspects of multisensory integration are achieved across this temporal hierarchy of integration phases. The work of Yau *et al.* [3] provides some very nice predictions that can now be tested by the neurophysiology and neuroimaging communities.

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DOI: 10.1016/j.cub.2009.03.029

Necrosis: C-Type Lectins Sense Cell Death

Recent studies have shown that C-type lectins, a family of surface receptors known to recognize microbial carbohydrate moieties, also sense products from dying cells and transduce inflammatory signals that modulate the immune system.

Alessandra Cambi and Carl Figdor*

During embryonic development and throughout the life of multicellular organisms many cells die, either during tissue remodeling, or because of injury, or at sites of mechanical stress.
Two main types of cell death can be distinguished. Apoptotic cell death — also termed homeostatic cell death — is a physiological event that is important during development and maintenance of tissues. Apoptosis is an active and energy-conserving form of cell death that eradicates aged or diseased cells and poses little threat to the organism. This death process therefore must not lead to activation of the immune system but rather to quick clearance of the dying cells by phagocytes without concomitant induction of inflammatory responses. By contrast, cell death